Next-generation VLBI model: higher accuracy and larger baselines

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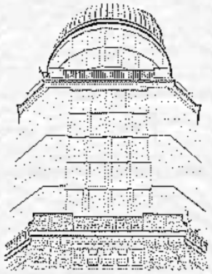


JD7, Beijing, 28 August 2012

What do we have?

+ Consensus VLBI model is given in the IERS Conventions since 1992:

  Quasars only (no parallax, no proper motion),
  Earth-bound baselines (up to 12000 km),
  1 ps accuracy for the group delay

+ Several published models going beyond the Consensus model used “from time to time”, not always self-consistent

However:

- VLBI accuracy is gradually increasing
- VLBI is extensively used for Galactic sources
- Space VLBI is progressing (Radioastron, etc.)
- Extensive use of Delta-DOR (Delta Differential One-Way Ranging) for space navigation

What do we need?

A more accurate and more general VLBI model is needed

- increased accuracy: at least 0.1 ps for Earth-bound baselines

- valid for much larger baselines: up to 1 million km or more

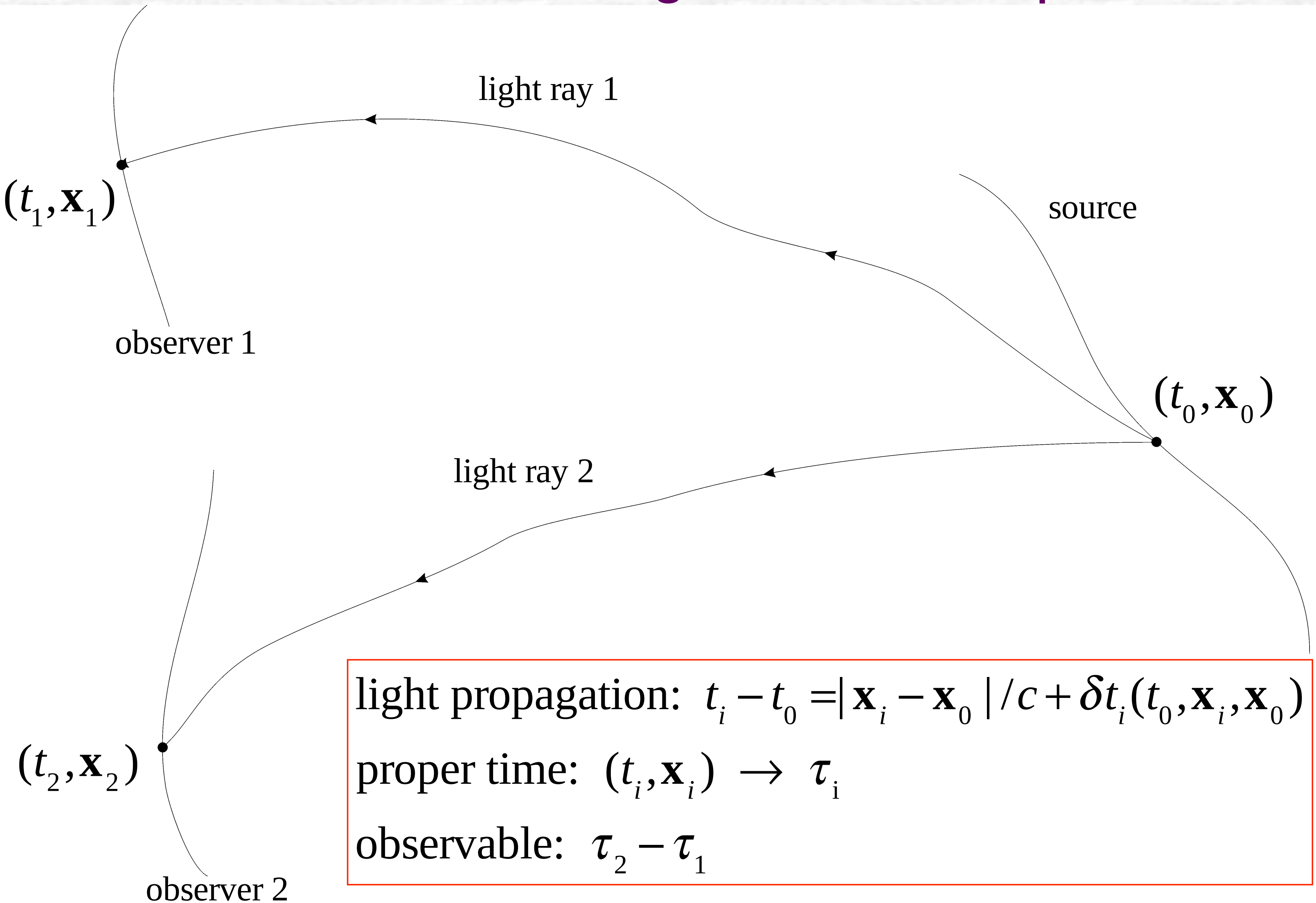
- valid not only for quasars, but for any class of sources

The idea of this work

Use the principles of GREM – Gaia Relativity Model –
to construct a generic (modular) next-generation VLBI model:

- Consistent use of the IAU relativistic framework
- Relativistic definition of all parameters and auxiliary data
- Direct numerical computation whenever possible
  (no unnecessary analytical approximations)
- Advanced modelling of signal propagation
- Standard astrometric model(s) for the motion of the sources
- An algorithm rather than a formula!
- Modular structure: depending on the kind of object, the observers and the requested accuracy, parts of the model (= modules) should be activated or deactivated

VLBI observable: generic description



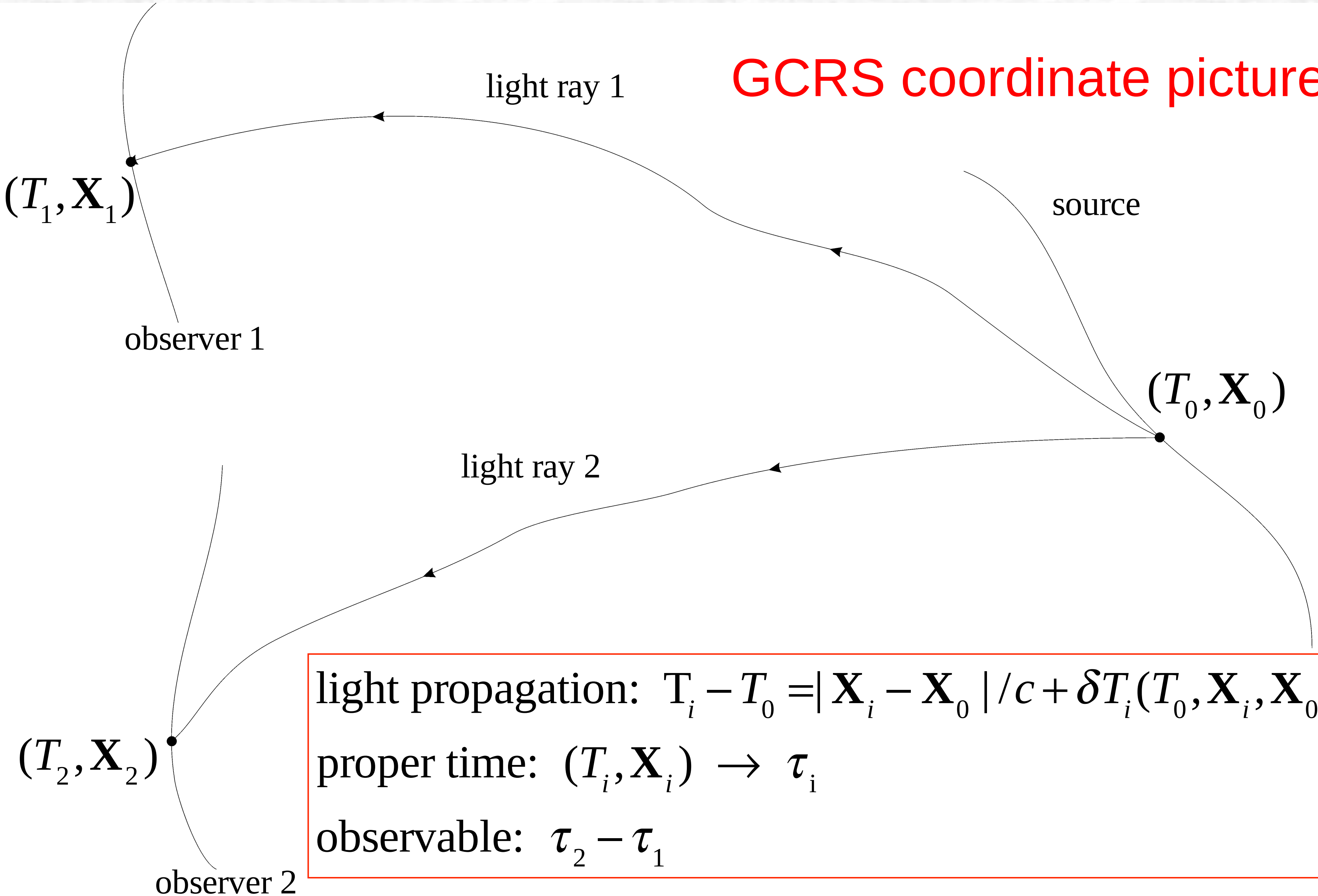
light propagation: $t_i - t_0 = |\mathbf{x}_i - \mathbf{x}_0| / c + \delta t_i(t_0, \mathbf{x}_i, \mathbf{x}_0)$

proper time: $(t_i, \mathbf{x}_i) \rightarrow \tau_i$

observable: $\tau_2 - \tau_1$

Case 1: Earth satellites

GCRS coordinate picture



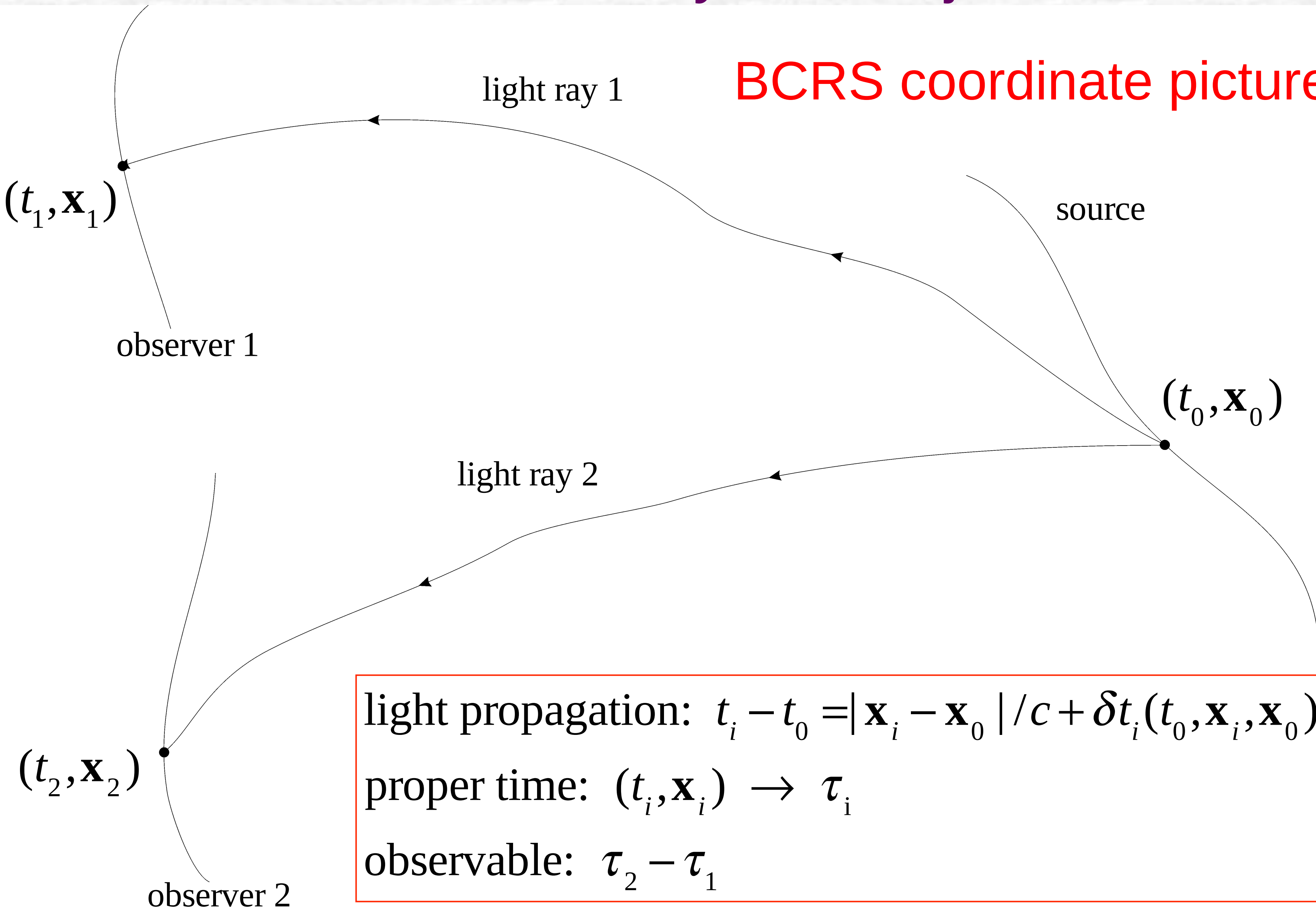
light propagation: $$\mathrm{T}_i - T_0 = |\mathbf{X}_i - \mathbf{X}_0| / c + \delta T_i(T_0, \mathbf{X}_i, \mathbf{X}_0)$$

proper time: $$(T_i, \mathbf{X}_i) \rightarrow \tau_{\mathrm{i}}$$

observable: $$\tau_2 - \tau_1$$

Case 2: solar system objects

BCRS coordinate picture



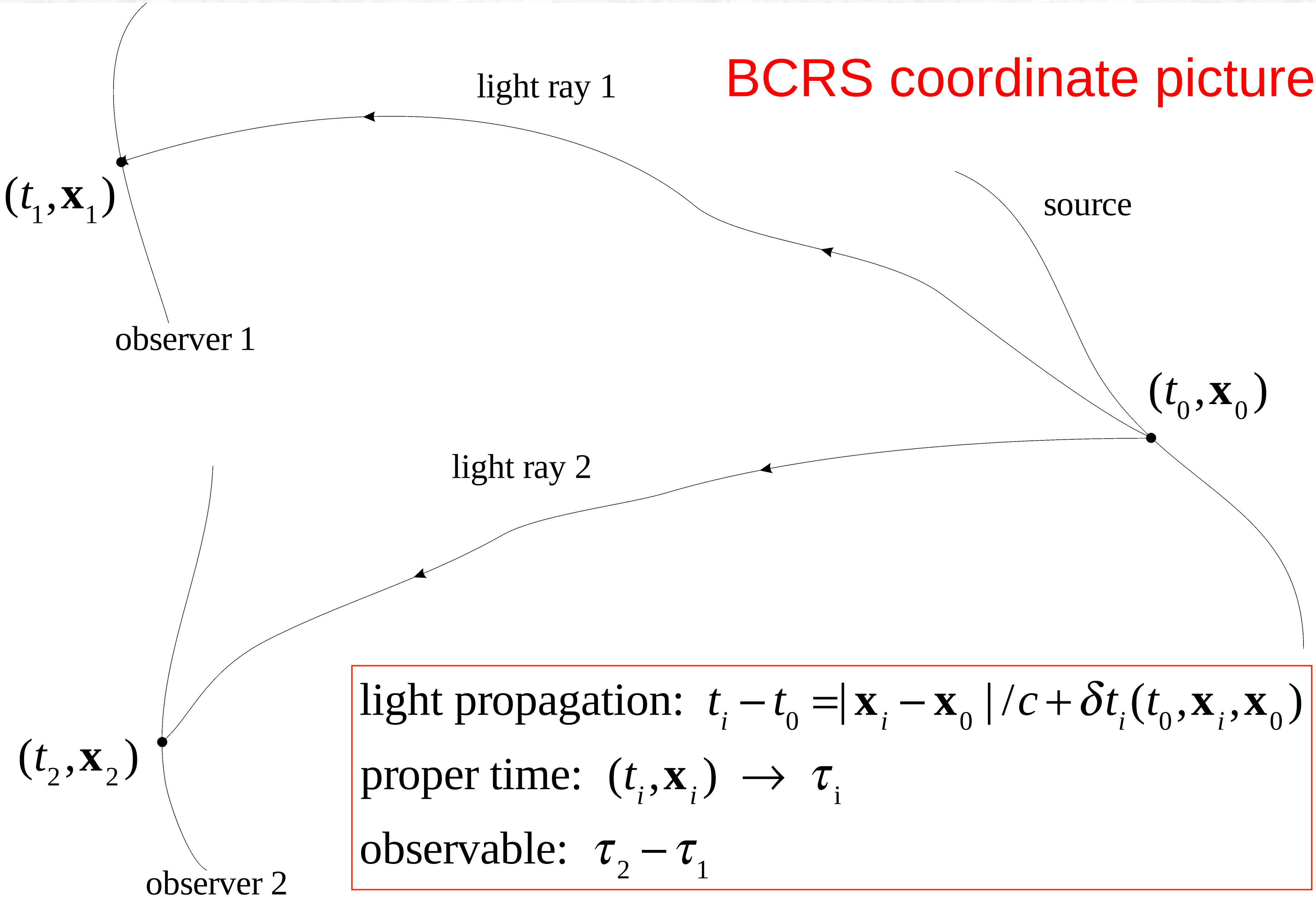
light propagation: $t_i - t_0 = |\mathbf{x}_i - \mathbf{x}_0| / c + \delta t_i(t_0, \mathbf{x}_i, \mathbf{x}_0)$

proper time: $(t_i, \mathbf{x}_i) \rightarrow \tau_\mathrm{i}$

observable: $\tau_2 - \tau_1$

Case 2: standard astrometric sources

BCRS coordinate picture

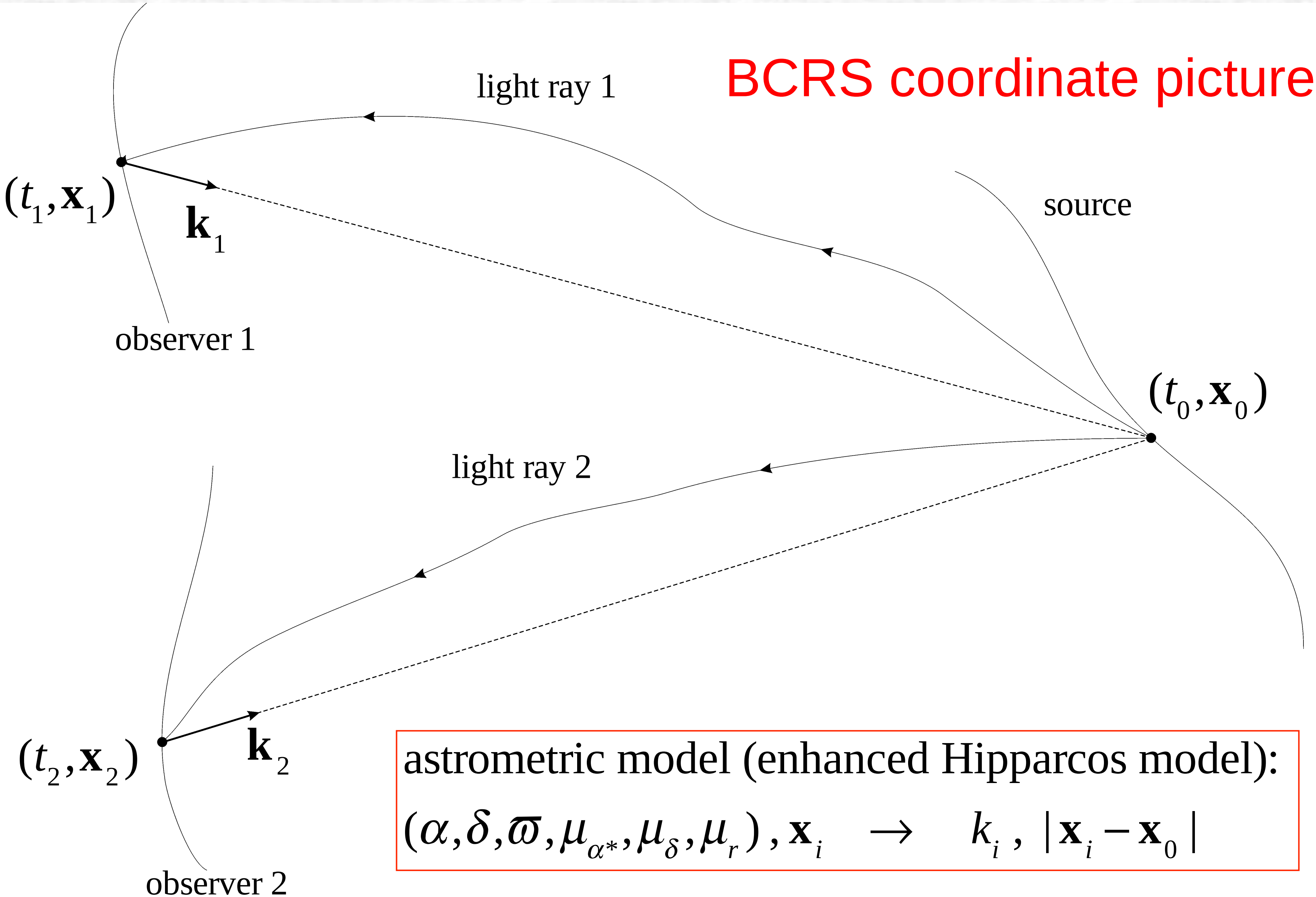


light propagation: $t_i - t_0 = |\mathbf{x}_i - \mathbf{x}_0| / c + \delta t_i(t_0, \mathbf{x}_i, \mathbf{x}_0)$

proper time: $(t_i, \mathbf{x}_i) \rightarrow \tau_\mathrm{i}$

observable: $\tau_2 - \tau_1$

Case 3: standard astrometric sources



astrometric model (enhanced Hipparcos model):

$$(\alpha, \delta, \varpi, \mu_{\alpha *}, \mu_\delta, \mu_r), \mathbf{x}_i \quad \rightarrow \quad k_i \,,\; |\mathbf{x}_i - \mathbf{x}_0|$$

Overview of further modules

1. Motion module for low-distance sources:

starting from a theory of motion in BCRS (or GCRS)

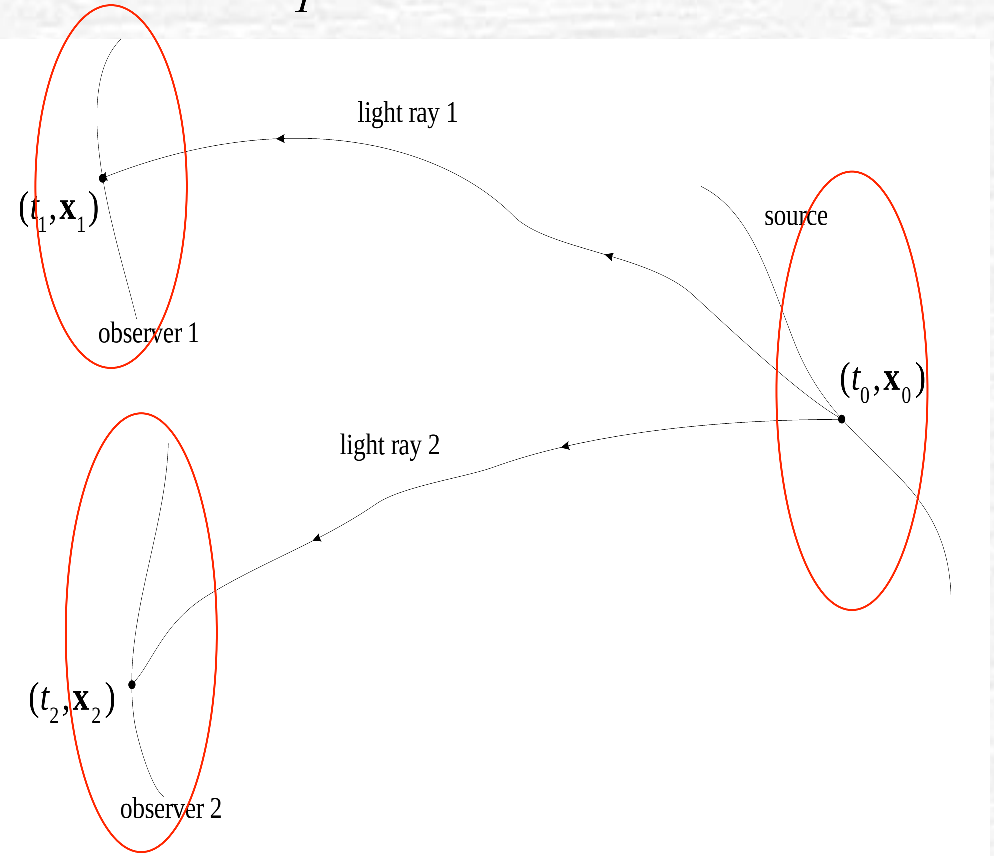
$$\mathbf{x}_{observer1}(t), \quad \mathbf{x}_{observer2}(t), \quad \mathbf{x}_{source}(t)$$

of the source and observers and t_1 determine the coordinates of three events

$$(t_1, \mathbf{x}_1)$$

$$(t_2, \mathbf{x}_2)$$

$$(t_0, \mathbf{x}_0)$$



One-way Shapiro delay is used here!

Overview of further modules

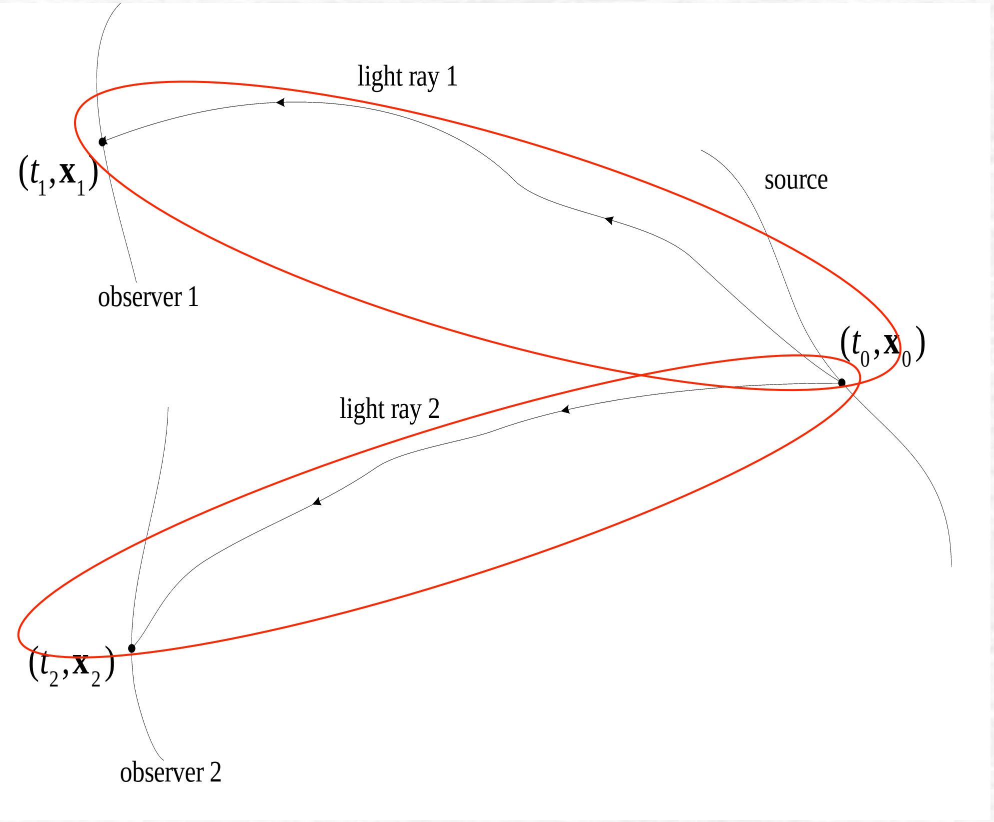
2. Light propagation: “one-way” and “differential for a baseline”

- post-Newtonian and (enhanced) post-post-Newtonian effects (Klioner, Zschocke, 2010, Class.Quantum Grav., 27, 075015)

- translation motion terms

- rotational motion terms

- non-sphericity terms



Important feature:
for many terms an upper estimate can be found for any baseline. E.g.

$$\left(\delta t_2 - \delta t_1\right)_{\text{quadrupole}} \le 6 J_2^A G M_A / c^3$$

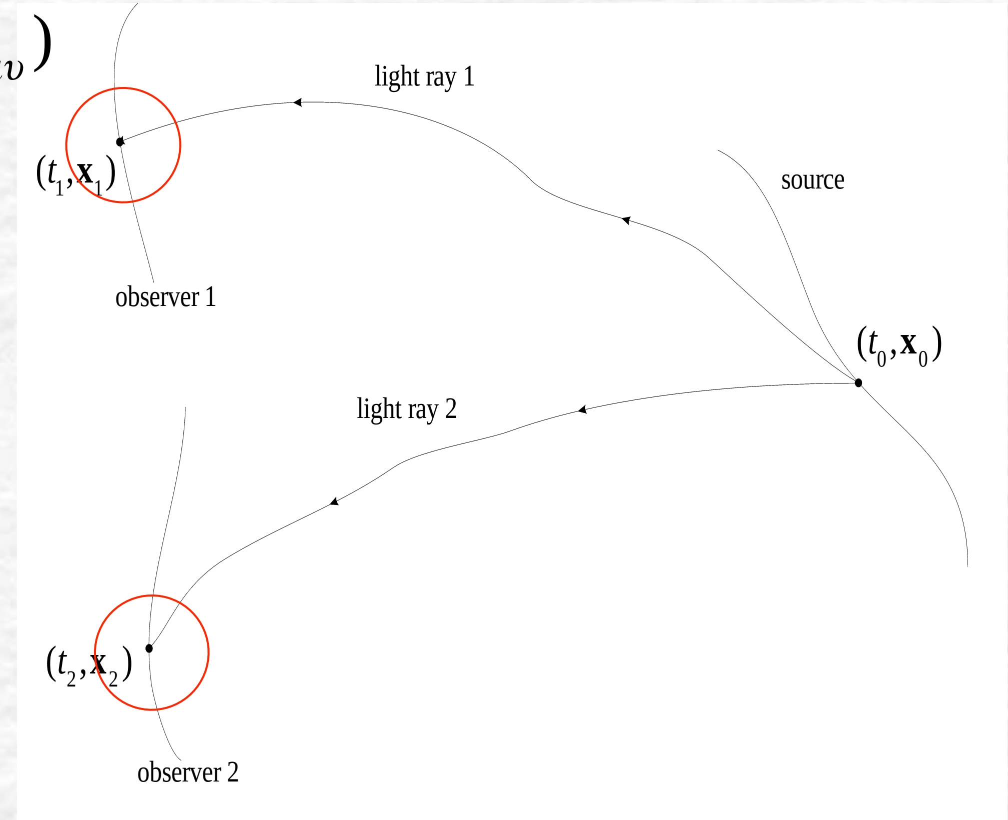
Overview of further modules

3. Relativistic time transformations:

a set of formulas and algorithms to transform between

UTC, TAI, TT, TDB, TCB, TCG and proper times of each observer

$$\tau_{\text{observer}} = \tau_{\text{observer}}(t, \mathbf{x}_{\text{observer}}(t); g_{\mu\upsilon})$$

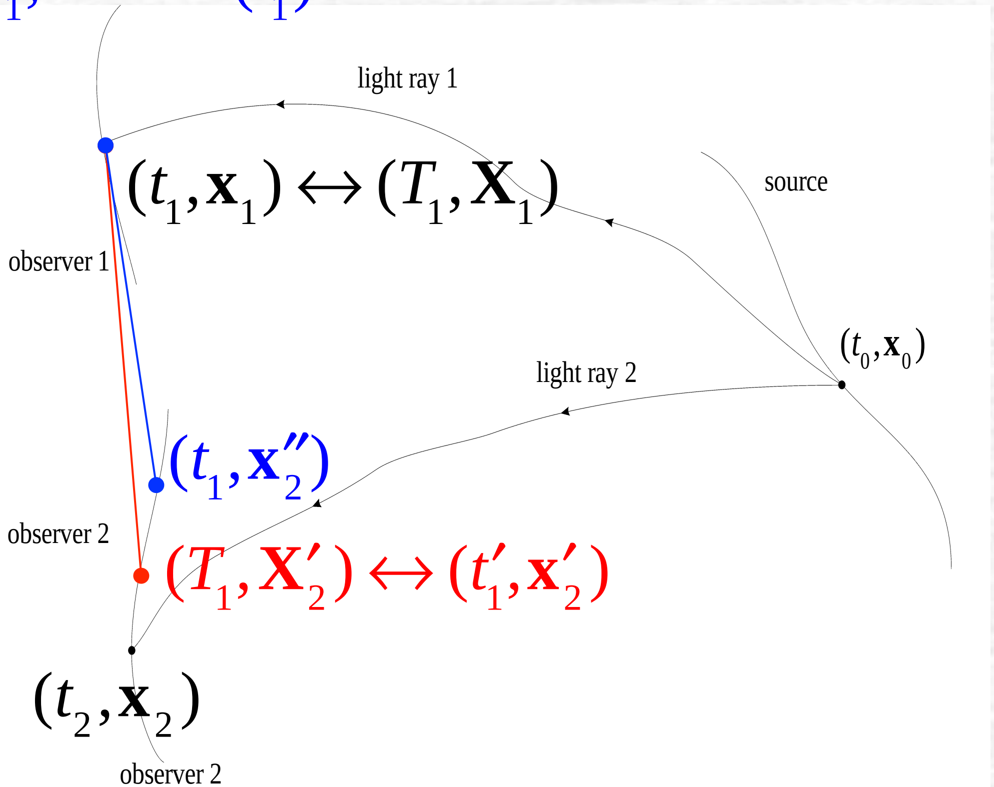


Overview of further modules

4. Transformation of the baseline for Earth-bound observers

Standard approach:

- GCRS baseline $\mathbf{B} = \mathbf{X}_2' - \mathbf{X}_1, \quad \mathbf{B} = \mathbf{B}(T_1)$
- BCRS baseline $\mathbf{b} = \mathbf{x}_2'' - \mathbf{x}_1, \quad \mathbf{b} = \mathbf{b}(t_1)$



- BCRS-GCRS transformations for the events:

$$(t, \mathbf{x}) \quad \leftrightarrow \quad (T, \mathbf{X})$$

Overview of further modules

4. Transformation of the baseline for Earth-bound observers

Standard approach:

- GCRS baseline $\mathbf{B} = \mathbf{X}_2' - \mathbf{X}_1, \quad \mathbf{B} = \mathbf{B}(T_1)$
- BCRS baseline $\mathbf{b} = \mathbf{x}_2'' - \mathbf{x}_1, \quad \mathbf{b} = \mathbf{b}(t_1)$

- From the BCRS-GCRS transformations:

$$
\begin{aligned}
\mathbf{b} &= \mathbf{B} - \frac{1}{c^2}\left(\frac{1}{2}\left(\mathbf{B}\cdot\mathbf{v}_E\right)\mathbf{v}_E + \left(\mathbf{B}\cdot\mathbf{v}_E\right)\dot{\mathbf{X}}_2 + \bar{w}_E\left(\boldsymbol{x}_E(t_1)\right)\mathbf{B}\right) \\
&+ \frac{1}{c^2}\left(\frac{1}{2}\left(\mathbf{B}\cdot\left(\mathbf{X}_1+\mathbf{X}_2\right)\right)\mathbf{a}_E + \mathbf{X}_2\left(\mathbf{X}_2\cdot\mathbf{a}_E\right) - \mathbf{X}_1\left(\mathbf{X}_1\cdot\mathbf{a}_E\right)\right) \\
&+ \frac{1}{c^4}\left(\text{post-post-Newtonian terms: Klioner, Xu et al 2012}\right)
\end{aligned}
$$

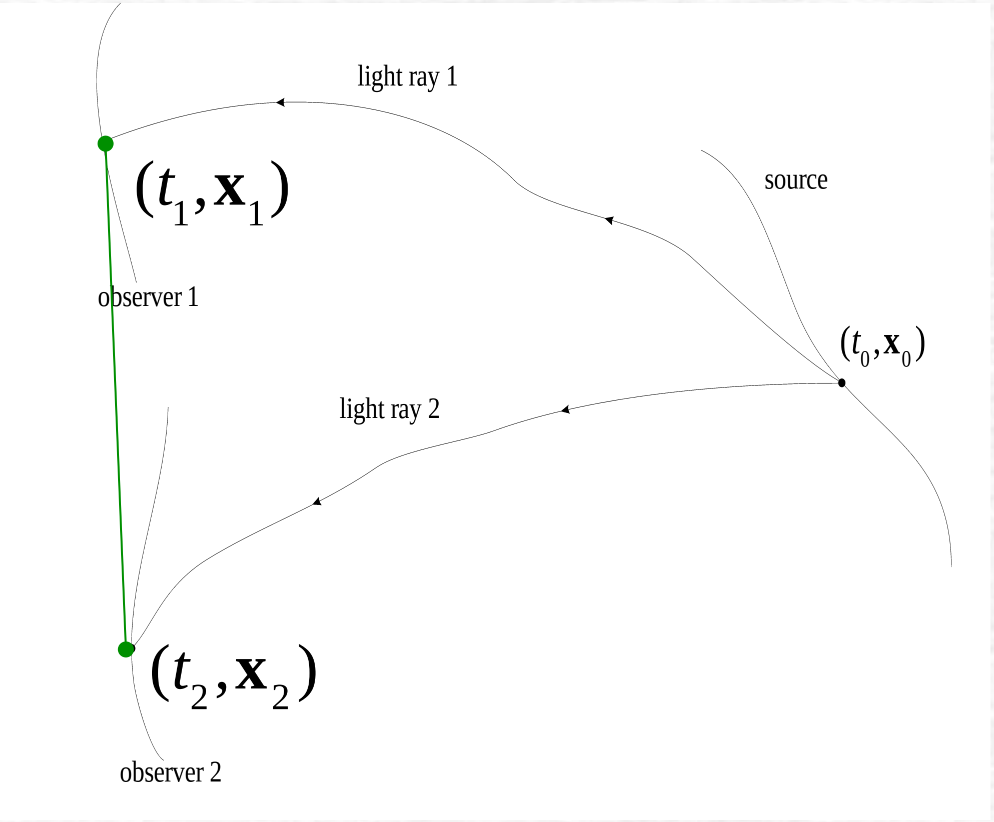
Overview of further modules

4. Transformation of the baseline for Earth-bound observers

Direct approach:

- GCRS coordinates (ITRS + rotation): $\mathbf{X}_{observer\,1}(T), \quad \mathbf{X}_{observer\,2}(T)$
- BCRS coordinates from a direct application of the BCRS-GCRS transformations for the events:

$$(t_1, \mathbf{x}_1) \quad \leftrightarrow \quad (T_1, \mathbf{X}_1)$$
$$(t_2, \mathbf{x}_2) \quad \leftrightarrow \quad (T_2, \mathbf{X}_2)$$



A generic high-accuracy VLBI model

is to be published soon